Assessing local materials for the treatment of wastewater in open drains

Priyanka Jamwal, Daniel Phillips and Kim Karlsrud

ABSTRACT

In the present study, three low-cost filter aggregate materials were tested and compared for organic matter and fecal coliform (FC) removal at the laboratory scale. Setups were subjected to synthetic wastewater at two hydraulic loading rates (HLR), i.e. 4 cm/day and 40 cm/day. The hydraulic retention time (HRT) at the two HLRs varied from 4 days to 12 h, respectively. The result obtained shows that the biochemical oxygen demand (BOD_5) removal efficiency of aggregate materials decreased with the increase in HLR. Both at high and low HLR, the terracotta aggregate material exhibited maximum BOD_5 loading removal and without significant difference for the case of FC removal efficiency for all the three aggregate materials. At higher HLR, cell debris and biofilm loss from the aggregate material contributed to the chemical oxygen demand (COD) levels in the treated water. The terracotta aggregate material provided best organic matter removal at both HLRs. The study demonstrates the potential of incorporating inexpensive and readily available local materials into decentralized, frugal green infrastructure interventions capable of lowering the quantum of harmful biological contaminants in open storm water channels in rapidly urbanizing cities of developing countries, and that the terracotta aggregate material provided best organic removal at both HLRs.

Key words | filtration, green infrastructure, megacities, storm drains, terracotta, wastewater

Priyanka Jamwal (corresponding author)
Centre for Environment and Development,
Ashoka Trust for Research in Ecology and the Environment (ATREE),
Jakkur, 560064,
India
E-mail: *priyanka.jamwal@atree.org*

Daniel Phillips
COMMONstudio (http://www.thecommonstudio.com/), With support from the U.S. Fulbright Program (Fulbright-Nehru Fellowship), which is co-sponsored by USIEF (United States-India Educational Foundation)

Daniel Phillips
Kim Karlsrud
School for Environment and Sustainability (SEAS),
University of Michigan,
State Street,
Ann Arbor, MI 48109,
USA

INTRODUCTION

Explosive urban growth throughout India and elsewhere in the global south continues to exert extreme pressure on urban wastewater systems, threatening human health, natural ecosystems, and livelihoods. Despite numerous laws, regulations and apocalyptic headlines, the widespread unchecked dumping of contaminated wastewater from domestic and industrial sources into urban lakes and streams will likely continue into the foreseeable future, as will it's associated impacts on public health (Jumbe & Nandini 2009; Ramachandra *et al.* 2015; Jamwal 2017). The interconnected nature of urban hydrological infrastructure means that many common domestic and industrial contaminants such as excess organic matter, biological oxygen demand (BOD_5), nutrients (nitrogen and phosphorus), trace metals, fecal coliforms (FC) and disease causing microorganisms tend to hyper-accumulate as they make their way through the system, causing a range of human and environmental health impacts downstream (Suthar *et al.* 2010; Jamwal *et al.* 2015). This includes lake eutrophication, fish kills, toxic foam, fire events, and downstream agricultural contamination. The implications of degraded urban surface water impacts stakeholders from across the socio-economic spectrum, and may impact the very viability of many burgeoning megacities in the near future (Bhasthi 2017). Larger infrastructural responses are required, and in some cases being implemented, but are often not scaling fast enough to keep pace with this growing crisis (Jamwal 2018). Inadequate investment, training and maintenance often limits the performance of existing large scale, technologically intensive infrastructures such as sewage treatment plants (Morel 2006; Jamwal *et al.* 2015). These realities underscore the urgent need for more frugal, flexible, decentralized responses aimed at supplementing existing efforts from the bottom up.

Elsewhere in the world, the notion of green infrastructure (GI) has gained much as a response to the issues of urban watershed contamination (Mell 2010; Kato 2011). GI is often modelled after naturally occurring wetland ecologies

doi: 10.2166/wst.2019.105

and deployed to reduce peak flows and reduce harmful pollutants in urban wastewater (Pisoeiro *et al.* 2016). Much of the existing GI research of water quality tends to focus on the performance of introduced vascular plants and macrophytes as tertiary treatment systems (Horppila & Nurminen 2001; Demırezen & Aksoy 2004; Malarvizhi *et al.* 2010; Pisoeiro *et al.* 2016). However, in developing countries such as India, urban storm water and domestic wastewater systems are often interwoven into an informal combined sewer overflow (CSO) system in which primary and secondary treatment is either non-existent or inconsistently provided (Morel 2006; Tortajada 2016). Moreover, urban wastewater systems in many Indian megacities is subject to high levels of 'infrastructural disarray', marked by many hidden failures and inefficiencies at various scales (Alley *et al.* 2018). In such a system, conventional approaches to GI are inadequate and inappropriate. New approaches are necessary that account for the myriad constraints presented by South Asian megacities.

What alternative approaches to GI might be possible for the developing world? How might we design more frugal, flexible and inclusive modes of GI which could be easily installed by local communities to compliment top-down infrastructures such as conventional wastewater treatment plants? Existing literature in the field of water science demonstrates that significant reductions in BOD_5 and total suspended solids (TSS) could be achieved even in unplanted (i.e. 'control') constructed wetland systems, which were likely achieved through the ability of basic material substrates to accommodate the growth of biofilms (Weerakoon *et al.* 2013; Pisoeiro *et al.* 2016). These insights suggest that the intentional introduction of 'disruptive' material aggregates into uncovered urban wastewater channels (referred to locally as 'Nallahs') may have the potential to provide immediate benefits to water quality (Prominski *et al.* 2012; Bhatnagar 2017). The objective of this study is therefore to add robustness to this emerging field of GI innovation in the Indian context by evaluating the comparative decontamination performance of a variety of basic, readily available aggregate materials which could be cheaply and easily introduced into urban wastewater channels. The novel approach explored in this study is to better understand how higher and more variable hydraulic loading rate (HLR) and hydraulic retention time (HRT) impact the removal efficiency of these filtration processes, and thus their likely performance in the context of real-world 'instream' interventions. Insights from this laboratory-based research are being leveraged to inform the design and implementation of small scale watershed interventions within the southern Indian city of Bangalore.

MATERIAL AND METHODS

Experimental setup

Subsurface filtration systems were set up to evaluate the contaminant removal efficiencies of three aggregate materials: terracotta, gravel, and cinder. These materials are inexpensive and readily available in the market and have distinct characteristics which make them suitable for treating wastewater. Terracotta is a lightweight porous material, cinder is a low strength material with substantial porosity, and gravel is a high-density material with low porosity (Yang *et al.* 2017). These materials have been used in bio-filters for treating domestic wastewater in the past (Lekang & Kleppe 2000; Tekerlekopoulou & Vayenas 2008).

The study was conducted by running synthetic wastewater through these material substrates at a variety of HLRs to compare their relative decontamination performance and potential. The experimental setup is illustrated in Figure 1, consisting of two overhead tanks, one for mixing and one for distribution (150 L and 200 L respectively). These tanks were gravity fed into three 'filter units', comprised of heavy duty rectangular plastic tubs measuring 940 mm (L) × 630 mm (W) × 535 mm (H) filled uniformly with material aggregates. Aggregate pieces ranged from 40–90 mm in approximate size and were all obtained from local construction sites at a nominal cost.

Synthetic wastewater

Synthetic wastewater was prepared using the mixture of urea, sugar, ammonium chloride, potassium phosphate, and FC culture prepared at ATREE's Water and Soil Laboratory. The quantities of constituents added per liter of water are presented in Table 1. For the preparation of synthetic wastewater, these constituents were thoroughly mixed and added to overhead storage tanks used in the experimental setup.

Table 2 presents the characteristics of the synthetic wastewater. The BOD_5, chemical oxygen demand (COD), ammonia-N, nitrates, and FC levels in the synthetic wastewater were similar to the theoretical levels estimated using the stoichiometric equations.

System operation

The BOD_5, COD, ammonia-N and FC levels in the synthetic wastewater represented the wastewater quality encountered in the open storm drains in the city of Bangalore (Jamwal

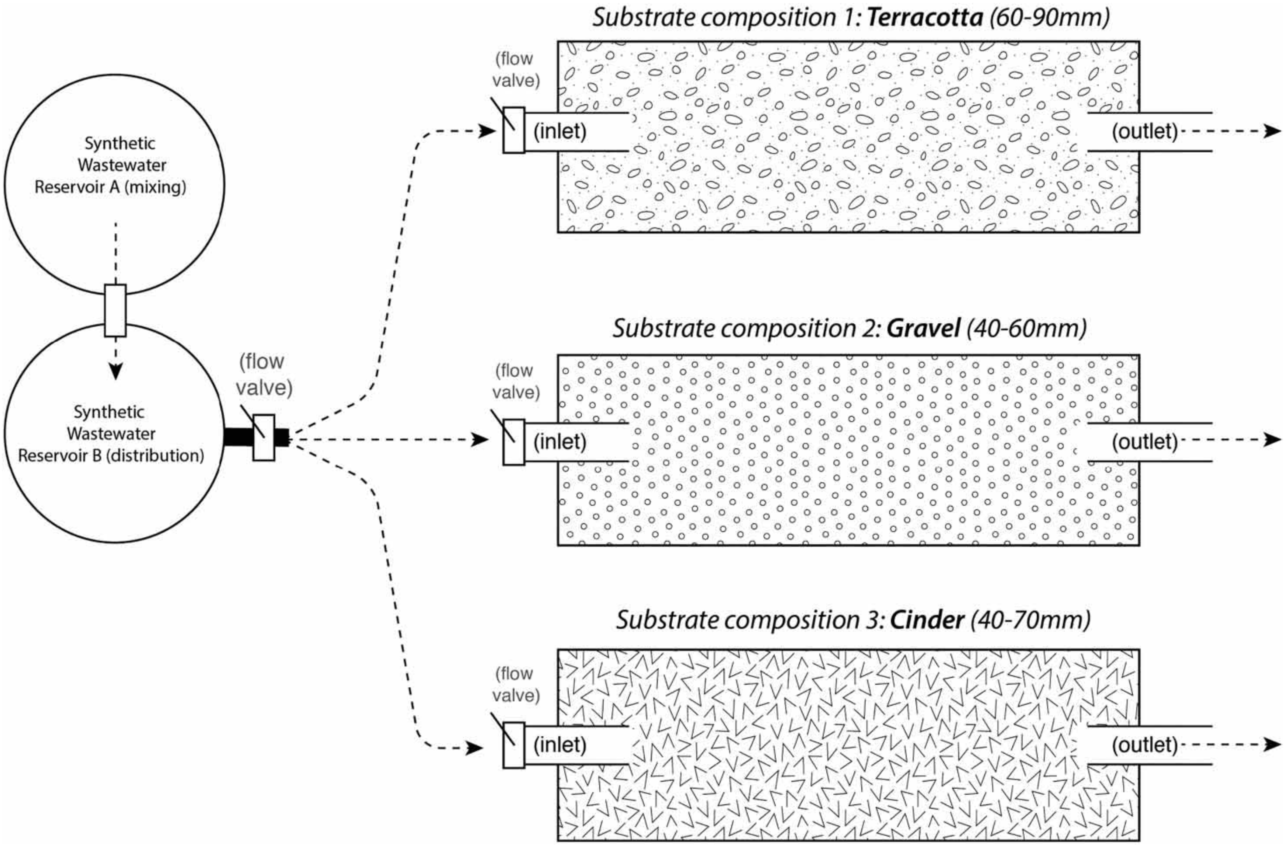

Figure 1 | The experimental setup.

et al. 2015). The effectiveness of filtration setups was evaluated at two HLRs: 4 cm/day and 40 cm/day. The HRT was estimated considering the porosity of the filter media (0.60). Table 3 presents the HRT at different HLRs.

The experimental setup consists of two tanks: the storage tank and the distribution tank (Figure 1). The storage tank was connected to the distribution tank with a check valve. The check valve was mounted on the distribution tank to maintain the constant HLR in the filtration setups. Throughout the experiment, the water depth in the distribution tank remained constant, and the storage tank was filled manually after a fixed interval of time.

Table 1 | Composition of the synthetic wastewater

Compounds	Quantity added/L
Sugar	0.53 g
Urea	0.005 g
NH_4Cl	0.117 g
KH_2PO_4	0.010 g
FC (suspended in NaCl)	0.1 ml

For acclimatization, the filtrations setups were fed with synthetic wastewater initially for three weeks. After the third week, the filtration setups were operated at two HLRs, i.e. 4 cm/day and 40 cm/day for six weeks each. The evaluation period (six weeks) selected was determined according to those observed in studies used by Chen *et al.* (2006), Chyan *et al.* (2013) and Ghosh & Gopal (2010).

Table 2 | Characteristics of the synthetic wastewater at two hydraulic loading rates

	Synthetic wastewater	
Water quality	Mean ($n = 6$) ± Std. Dev (HLR-4 cm/day)	Mean ($n = 4$) ± Std. Dev (HLR-40 cm/day)
pH	6.67 ± 0.56	7.67 ± .08
Conductivity (μS/cm)	1,733 ± 40	1,645 ± 29
BOD_5 (mg/L)	273 ± 46	250 ± 25
COD (mg/L)	396.0 ± 46.7	397.5 ± 35.8
Ammonia – N (mg/L)	28.8 ± 6.4	25.5 ± 4.5
Nitrate – N (mg/L)	6.90 ± 7.8	9.30 ± 10.5
$Log_{10}FC$ (MPN/100 mL)	5.67 ± 0.82	5.60 ± 0.68

Table 3 | Experimental design for efficiency evaluation of filtration setup

HLR (cm/day)	Influent flow rate (l/day)	HRT (day)	Maximum loading rate (MLR)				Overhead tank refilling frequency
			Ammonia – N (g/m^2/day)	BOD_5 (g/m^2/day)	COD (g/m^2/day)	FC (MPN m^2/day)	
4	22.6	4	1.1	8	13.2	$8*10^5$	Once in two days
40	226	0.5	10.3	112	168	$3*10^9$	Two times in a day

Assessment of organic matter and FC removal efficiencies

Pollutant removal efficiencies were evaluated by collecting water samples weekly twice at the inlet and the outlet of the three filtration setups. Samples were analyzed for BOD_5, COD, ammonia-N, nitrates and FC concentration. Standard methods for the examination of water and wastewater were followed to test the water quality parameters (APHA 2005). Removal efficiencies were calculated as a percentage reduction in the concentration from influent to the effluent samples using Equation (1). The corresponding mass loading rates (MLR) and mass removal rates (MRR) were also estimated. The MLR and MRR for the BOD_5, COD and FC were calculated using Equations (2) and (3).

$$\text{Removal efficiency (RE)} = \frac{(C_i - C_o)}{C_i} \times 100 \quad (1)$$

$$\text{Mass loading rate} = (C_i - C_o) \times (\text{HLR}) \quad (2)$$

$$\text{Mass removal rate (MRR)} = (C_i - C_o) \times (\text{HLR}) \times 100 \quad (3)$$

where C_i = concentration of contaminant in the influent and C_o = concentration of the contaminant in the effluent.

Statistical tests

Significant differences in the contaminated removal efficiencies of three aggregate materials subjected to different HLRs were evaluated using one-way analysis of variance (ANOVA) test for the normally distributed data at 0.05 significant levels. The correlation between the MLR and the MRR were identified using linear regression.

RESULTS AND DISCUSSION

Wastewater characteristics and effluent quality

The influent characteristics of synthetic wastewater are presented in Table 2. Significant variation in the influent quality was observed at lower HLR. This could be attributed to the longer refilling time of synthetic wastewater into the overhead tank. The biological transformation in the overhead and the distribution tanks may have caused variations in the quality of synthetic wastewater. Similar variations were reported in the studies where in synthetic sewage is used for carrying out experiments under controlled conditions (Weerakoon et al. 2013; Xu et al. 2018).

The effluent characteristics from three filter media setup are shown in Table 4. A statistical test (Kolmogorov-Smirnov) showed that the influent and effluent characteristics at different HLRs were normally distributed. The average, maximum and minimum contaminant levels in influent and the effluent of the setups were estimated. For FC, the data were converted into the log normal form for the analysis.

Figure 2 shows the levels of BOD_5, COD, ammonia-N, and FC in the influent and effluent during the course of the experiment. The BOD_5 represents the biodegradable component of organic matter and COD represents both the biodegradable and non-biodegradable component along with chemically oxidisable compounds present in the wastewater (Kim 1989). Ammonia-N represents the excess nutrients levels commonly present in domestic grey and blackwater. High ammonia-N levels in the effluent indicate poor nutrient removal capabilities of the treatment system. Presence of FC indicates the possible presence of pathogens in the source water.

The synthetic sewage represents characteristics of wastewater flowing in the open storm water channels. The average BOD_5, COD and FC levels are similar to the levels reported in Vrishabhavathy stream in the city of Bangalore (Jamwal et al. 2015). Considering the use of aggregate material for the removal of contaminants *in situ*, the pilot setup was exposed to very high to normal flow rates, i.e. ranging from 226 L/day to 22.6 L/day. These flow rates replicate the wastewater flows in the open storm water drains and corresponds to the 40 cm/day and 4 cm/day HLRs, respectively. Generally, the performance of subsurface treatment systems is tested at low contaminant loading rates (Mashauri et al. 2000; Chen et al. 2006; Ghosh & Gopal 2010). However, considering the application of this technology in treating highly

Table 4 | Water quality characteristics of effluent from three filtration setups

Water quality	Outlet 1 – Terracotta		Outlet 2 – Gravel		Outlet 3 – Cinder	
Parameter	HLR – 4 cm/m² Mean ± Std. Dev	HLR – 40 cm/m² Mean ± Std. Dev	HLR – 4 cm/m² Mean ± Std. Dev	HLR – 40 cm/m² Mean ± Std. Dev	HLR – 4 cm/m² Mean ± Std. Dev	HLR – 40 cm/m² Mean ± Std. Dev
pH	7.34 ± 0.33	7.3 ± 0.88	7.9 ± 0.38	7.5 ± 0.65	7.4 ± 0.44	7.5 ± 0.90
Conductivity (μS/cm)	1,779 ± 102.5	1,644 ± 121	1,669 ± 77	1,649 ± 94	1,704 ± 43	1,700 ± 140
BOD_5 (mg/L)	26 ± 15	69 ± 22	34 ± 24	81 ± 18	127 ± 43	102 ± 50
COD (mg/L)	104.2 ± 24.2	232.5 ± 84.2	115.8 ± 45.8	292.0 ± 100.1	143.3 ± 75.8	260 ± 117.4
Ammonia – N (mg/L)	17.0 ± 6.0	19.5 ± 2.0	14.5 ± 6.3	16.5 ± 1.2	22 ± 10	19.5 ± 1
Nitrate – N (mg/L)	1.7 ± 0.88	2.7 ± 2.0	1.2 ± 0.45	3.6 ± 4.2	1.0 ± 0.50	0.70 ± 1.17
$Log_{10}FC$ (MPN/100 mL)	3.3 ± 0.8	4.5 ± 1.0	3.7 ± 0.8	4.5 ± 0.6	3.7 ± 0.8	4.3 ± 1.0

contaminated flows in the channeled sections of the open storm water drains, the setups were exposed to medium to very high contaminants loading rates (Table 3).

Significant reductions in, BOD_5, COD and FC levels were observed in all three setups. Increase in the contaminants removal efficiency was observed at the higher HRT.

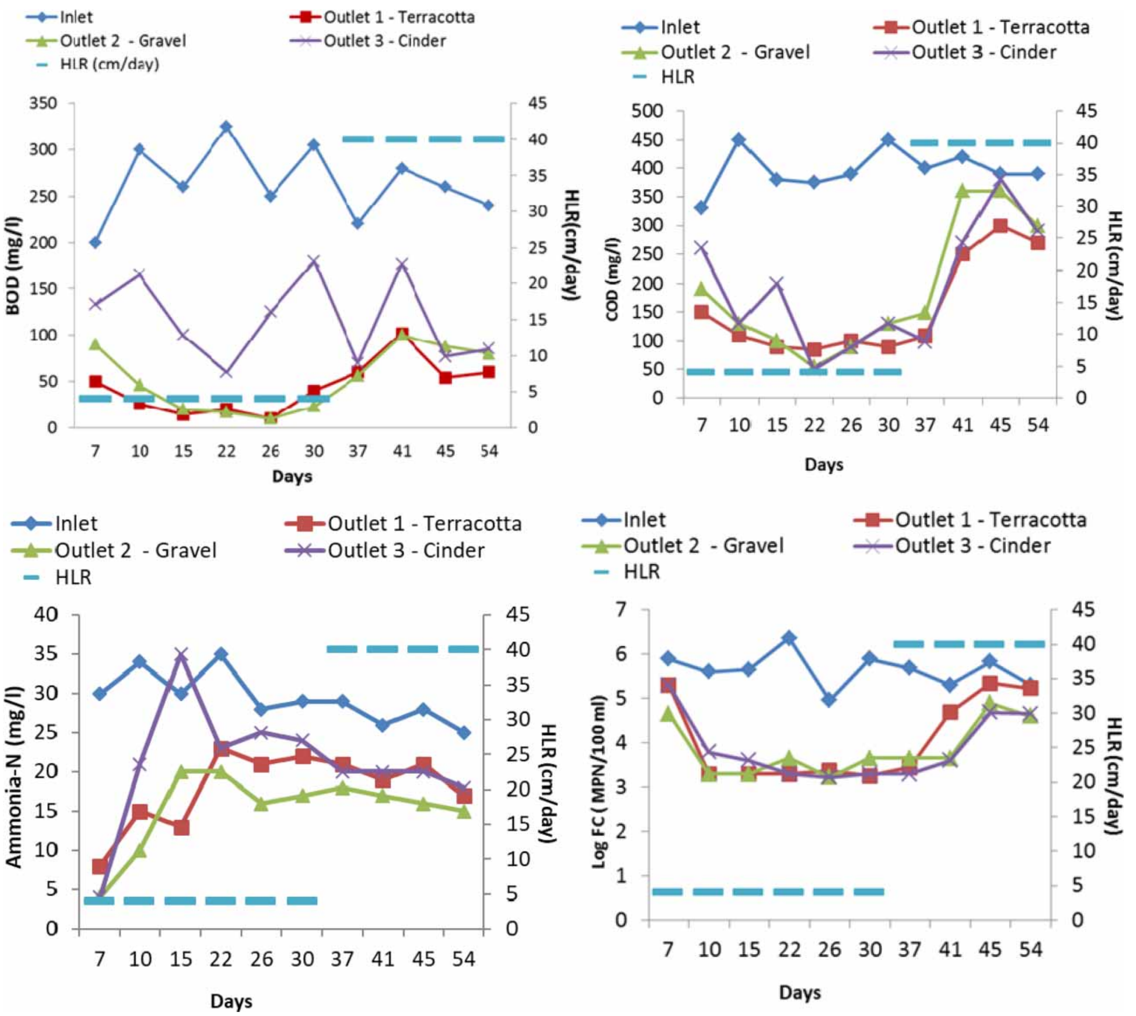

Figure 2 | Effluent quality from three filtration setup during the experiment at different HLR.

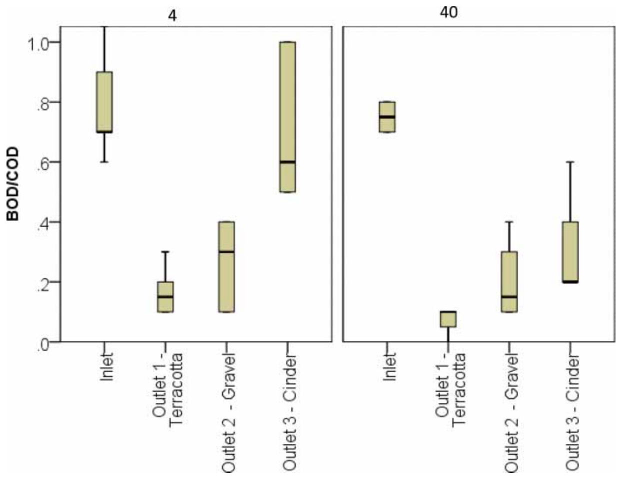

Figure 3 | BOD_5/COD ratio observed at two HLRs.

The COD levels observed in the influent and effluents were much higher than the BOD_5 levels. Given that glucose contributed primarily to the BOD_5 whereas both glucose and other chemically oxidisable compounds contributed to COD, the levels of COD observed were greater than the BOD_5. Various physical, chemical, and biological processes help in the removal of contaminants from the wastewater. Sedimentation and biological decomposition is mainly responsible for the removal of organic matter, i.e. COD and BOD_5.

The contaminant levels observed in the effluent from three setups followed a similar trend. As compared to lower HLR, poor effluent quality was observed at higher HLR, i.e. 40 cm/day. This could be attributed to a) increased flow velocities at high HLR and b) reduced contact time of contaminants with the filter media. At higher flow velocities, biofilm abrasion and removal of cell debris contributes to the COD. The effluent debris and biofilms are composed of complex organic matter that is hard to decompose and hence contributes to the COD (Behnke et al. 2011). Also, reduced contact time lowers the microbial degradation of organic matter present within the filtration system. BOD_5/COD ratio indicates the proportion of readily oxidisable organic matter present in the effluent. Figure 3 presents the BOD_5/COD ratio in the influent and effluent at different HLR. A drop in the average BOD_5/COD ratio was observed for gravel and cinder based filtration setups, whereas for terracotta, the BOD_5/COD ratio remain same at both high and low HLRs. This indicates the stable and abrasion resistant nature of biofilms formed on the terracotta material. Few studies have reported the impact of terracotta balls in removal of bacterial species and organic matter. One of the studies suggested that the biofilm formation on the terracotta balls in the slow sand filtration process is stable and effectively removes biodegradable organic compounds from the source water (Le Dantec et al. 2002).

Except for the cinder based filtration setup, higher reduction in the ammonia-N levels were observed at the low HLR (Table 5). The reduction of ammonia-N in the setups could be attributed to the biofilm formation within the system. The low levels of nitrate-N observed in the effluents suggests limited conversion of ammonia-N into nitrate-N. This suggests that in the absence of nitrification and plants, uptake of ammonia-N by heterotrophic bacteria for biofilm formation is major reason for its reduction (Ribot et al. 2013). Both terracotta and gravel setup exhibited similar removal efficiencies at lower HLR. However, at higher HLR, gravel setup exhibited the highest ammonia-N removal efficiency.

Out of the three materials tested, the terracotta based filtration setup produced the best overall quality effluent both at low and high HLR. Efficacy of terracotta material in treating surface and groundwater for drinking water purposes is well established. Various studies reported the effectiveness of terracotta material in reducing the organic carbon and coliphage in the drinking water (Low 2002; Franz 2005). At lower HLR, the BOD_5 and COD levels in the effluent from terracotta filtration system met effluent

Table 5 | Contaminant removal efficiency of three filtration setup at different HLRs

Removal efficiency	Outlet 1 – Terracotta		Outlet 2 – Gravel		Outlet 3 – Cinder	
Parameter	HLR – 4 cm/m^2 % Removal	HLR – 40 cm/m^2 % Removal	HLR – 4 cm/m^2 % Removal	HLR – 40 cm/m^2 % Removal	HLR – 40 cm/m^2 % Removal	HLR – 40 cm/m^2 % Removal
BOD_5 (mg/L)	90	76	86	68	54	59
COD (mg/L)	73	41	70	27	62	35
Ammonia – N (mg/L)	45	28	53	39	28	27
Log_{10}FC (MPN/100 mL) removal*	2	1.2	1.6	1.5	1.8	1.5

discharge standards for secondary treated water. No significant difference was observed in the FC levels of the effluent from all the three filtration setups. The ability of solar disinfection SODIS in reducing the *Escherichia coli* (*E. coli*) levels by 5 log orders in 2.5 h is well documented in literature (Lonnen *et al.* 2005). Given that the three setups were located outdoors and were equally exposed to the sunlight, the effect of ultraviolet radiation in removal of FC is likely more significant than the other mechanisms such as sedimentation, adsorption and natural die-off (Mashauri *et al.* 2000).

Pollutant removal efficiencies

Table 5 illustrates the Ammonia-N, BOD_5, COD and FC removal efficiencies of three filtration setups over the entire study period. The HRT at respective HLRs is reported in Table 3. With the exception of the cinder material filtration unit (where no significant difference was observed in the ammonia-N removal efficiencies at both low and high HLR), ammonia-N, BOD_5, COD and FC removal efficiency followed a similar trend, i.e. decrease in pollutant removal efficiency at higher HLR.

The organic matter removal mechanism in the filter media includes adsorption, sedimentation and microbial metabolism. Filter media with high porosity provides additional capacity as well as space and a favorable environment for microbial growth for better organic matter removal (Chyan *et al.* 2013). Further, porosity increases the adsorption of organic matter on the surface thereby improves the organic matter removal efficiency. The terracotta setup provided the highest BOD_5 and COD removal efficiency at both HLRs. In the case of gravel based filtration system, a significant drop was observed in BOD_5 and COD removal efficiency at high HLR. Of all three experimental setups, the cinder setup was found to be the least efficient. The poor efficiency of cinder aggregate material could be attributed to a significant drop in the BOD_5/COD ratio at high HLR. Also, the frequent peaks in the effluent BOD_5 and COD indicates the periodic abrasion of biofilm from the surface of cinder material (Figure 3). Ammonia-N removal is the function of biofilm response to N uptake on exposure to ammonia-N (Ribot *et al.* 2013). Given that both terracotta and gravel (to a lesser extent) exhibits stable and abrasion resistant biofilm, at lower HLR the ammonia-N removal efficiency in both is significantly greater than that of the cinder aggregate material.

Coliform removal mechanism in the filtration systems includes physical processes such as filtration, sedimentation,

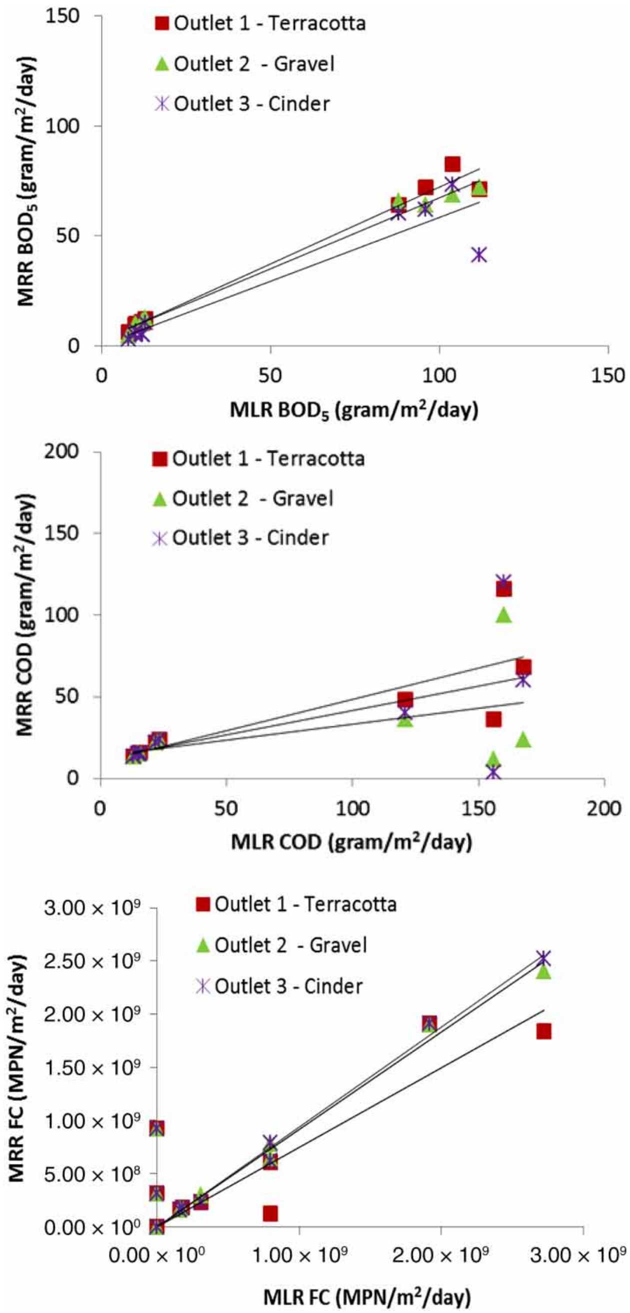

Figure 4 | Relationship between contaminant mass loading rate and mass removal rate.

ultraviolet radiation; chemical processes such as absorption, oxidation, natural die-off and die-off due to toxins and biological activities, as well as ingestion by nematodes and protozoa (Karim *et al.* 2004; Wu *et al.* 2016). It is believed that porosity and HRT has a significant impact on the settling of microorganisms within the filtration system. All the factors are interrelated, and apportioning contribution of each factor to the removal of FC is complex. At low

Table 6 | Mass loading rate and mass removal rate and corresponding R^2 values

Parameter	Units	MLR Influent	MRR Outlet 1 – Terracotta (R^2)	Outlet 2 – Gravel (R^2)	Outlet 3 – Cinder (R^2)
BOD_5	$g/m^2/day$	8–112	6–82 (0.99)	4.4–72 (0.98)	2.7–73 (0.88)
COD	$g/m^2/day$	13.2–168	7.2–116 (0.66)	5.6–100 (0.26)	2.8–120 (0.37)
FC	(MPN m^2/day)	8–27,200*10^5	7.2–19,088 *10^5 (0.84)	9.92000–24,040 *10^5 (0.82)	9.9–25,240 *10^5 (0.68)

HLR, terracotta based filtration system provided maximum FC removal, whereas at high HLR all three filtration setups provided similar FC removal levels. An ANOVA test was conducted to test the impact of filter material on FC removal efficiency. The results showed that filtration material does not have any effect on the FC removal efficiency. Factors such as exposure to sunlight and natural die-off facilitated FC removal in all three setups.

Figure 4 shows the relationship between incoming contaminant MLR and MRR for BOD_5, COD and FC. The relationship between MLR and MRR was determined to evaluate the effectiveness of filter media under varying contaminant loadings. Compared to previous studies, in this study, filtration setups were subjected to moderate to very high BOD_5 and COD loading rates (Table 6) (Ghosh & Gopal 2010; Weerakoon *et al.* 2013). The incoming contaminant load was increased significantly during the study period with HLR increment from 4 to 40 cm/day. Except for COD, a good linear correlation was observed between the incoming BOD_5 MLR (8–112 $g/m^2/day$) and the MRR with an R^2 value greater than 0.90. A moderate correlation was observed between the incoming COD MLR and MRR for the terracotta filtration setup ($R^2 = 0.67$), which could be attributed to the presence of stable and abrasion resistant biofilm. The FC removal rates (MPN/m^2/day) in all the three filtration setups showed a very strong linear correlation to the incoming loads with corresponding R^2 values of more than 0.98. The relationship suggests that for all aggregate material the BOD_5 and FC removal per unit of the BOD_5 and FC load applied is significantly higher than that of the COD.

Subsequent site based testing

The study described here is one part of an ongoing interdisciplinary effort currently underway in the city of Bangalore. Strategic Instream Systems (STRAINS) proposes decentralized, cost-effective solutions to the ongoing challenge of contamination within rapidly growing urban contexts (Figure 5). The results of these laboratory based tests suggest that the use of low-cost terracotta fragments may be an appropriate aggregate material to incorporate into larger scale interventions within the urban storm water channels ('Nallahs'). Subsequent intermediate scale demonstration sites will incorporate terracotta material as an integral part of their function. Subsequent field based tests and regular

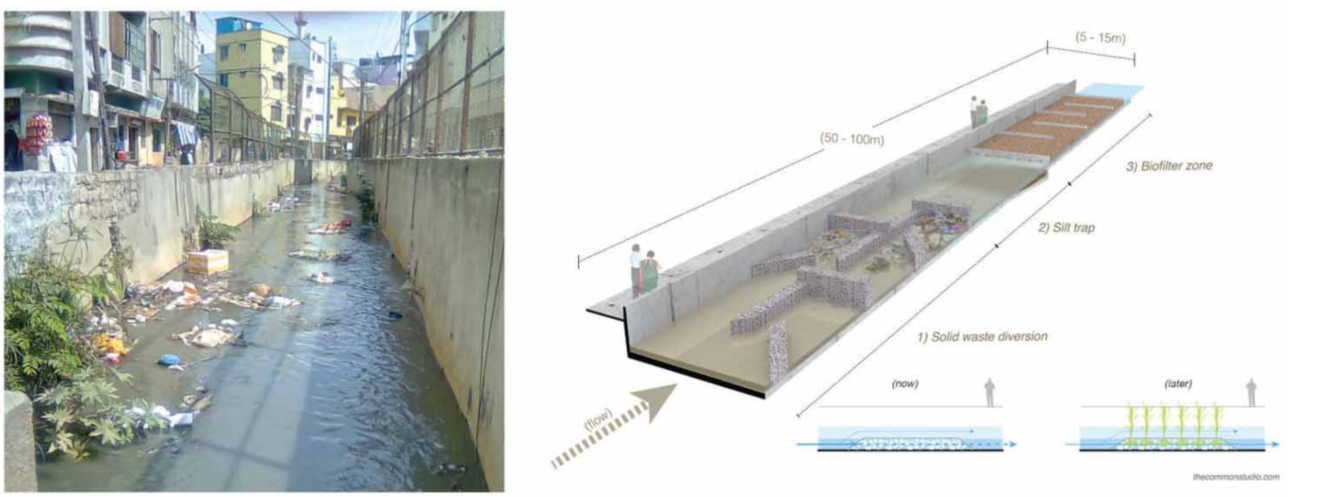

Figure 5 | Typical urban Nallah condition (left) and conceptual rendering of a three stage STRAINS intervention including terracotta filtration zone in the final stage.

water-quality monitoring will follow, which will provide deeper insights into its potentials and limitations of this approach.

CONCLUSIONS

The objective of the study was to assess the organic matter and FC removal efficiencies of horizontal subsurface filtration systems composed of three different aggregate materials: terracotta, gravel, and cinder. The setups were tested using synthetic wastewater prepared in the laboratory and contaminant removal efficiency was evaluated at different HLRs. From the results, the following was concluded:

(a) All three filtration materials followed similar trends in effluent quality. Significant reduction in the effluent quality was observed at high HLR, which could be attributed to reduced contact time of contaminants within the system due to increased flow velocities.

(b) At both high (40 cm/day) and low (4 cm/day) HLRs, the terracotta based filtration setup provided maximum reduction in COD and BOD_5 levels. Although at low HLR gravel based filtration system provided BOD_5 reduction similar to that of the terracotta based system, the terracotta based filtration system was found to be more efficient at higher HLRs.

(c) Both terracotta and gravel setup exhibited similar ammonia-N removal efficiencies at lower HLR. However, at higher HLR, gravel setup exhibited the ammonia-N removal efficiency. Out of three, the cinder based filter setup exhibited lowest removal efficiency at both low and high HLR.

(d) No significant difference was observed in the FC removal efficiencies of three filtration systems, indicating that filter material does not affect the FC removal from the wastewater.

(e) Except for COD, a strong correlation was observed in input BOD_5 and FC mass loading rate with the mass removal rate. The release of biofilm and cell debris at higher HLR would have contributed to considerable variation in the effluent COD from the three filtration systems.

(f) Significant reductions in organic pollutants may be possible using affordable aggregate biofilters in open storm water channels which are vectors for greywater, and that these reductions may be significant even in unplanted configurations. This suggests a low-maintenance approach as compared to traditional modes of GI or constructed wetlands, which typically promote the presence and maintenance of plants.

ACKNOWLEDGEMENTS

This research was supported by a research grant from the Royal Norwegian Embassy (RNE) and the Ashoka Trust for Research in Ecology and the Environment (ATREE). The authors would like to thank the Praveen Kumar (laboratory analyst), and Sowmya Murugan (intern from IISER) at ATREE for helping us with the analysis of water samples and maintenance and upkeep of the experimental setup.

REFERENCES

Alley, K. D., Barr, J. & Mehta, T. 2018 Infrastructure disarray in the clean Ganga and clean India campaigns. *Wiley Interdisciplinary Reviews: Water* **5**, e1310.

APHA 2005 *Standard Methods for the Examination of Water and Wastewater*, 21st edn. APHA, Washington, DC, USA.

Behnke, S., Parker, A. E., Woodall, D. & Camper, A. K. 2011 Comparing the chlorine disinfection of detached biofilm clusters with those of sessile biofilms and planktonic cells in single- and dual-species cultures. *Applied and Environmental Microbiology* **77**, 7176–7184. https://doi.org/10.1128/AEM.05514-11.

Bhasthi, D. 2017 City of burning lakes: experts fear Bangalore will be uninhabitable by 2025. Cities, The Guardian, 1 March.

Bhatnagar 2017 *INTACH Pilot Project Reduces Assi River Pollution in Varanasi by 70% in Two Months, at Least Cost, without any Structures*. SANDRP.

Chen, T. Y., Kao, C. M., Yeh, T. Y., Chien, H. Y. & Chao, A. C. 2006 Application of a constructed wetland for industrial wastewater treatment: a pilot-scale study. *Chemosphere* **64**, 497–502.

Chyan, J.-M., Senoro, D.-B., Lin, C.-J., Chen, P.-J. & Chen, I.-M. 2013 A novel biofilm carrier for pollutant removal in a constructed wetland based on waste rubber tire chips. *International Biodeterioration & Biodegradation* **85**, 638–645.

Demırezen, D. & Aksoy, A. 2004 Accumulation of heavy metals in *Typha angustifolia* (L.) and *Potamogeton pectinatus* (L.) living in Sultan Marsh (Kayseri, Turkey). *Chemosphere* **56**, 685–696.

Franz, A. 2005 *A Performance Study of Ceramic Candle Filters in Kenya Including Tests for Coliphage Removal*. PhD Thesis, Massachusetts Institute of Technology, Cambridge, MA, USA.

Ghosh, D. & Gopal, B. 2010 Effect of hydraulic retention time on the treatment of secondary effluent in a subsurface flow constructed wetland. *Ecological Engineering* **36**, 1044–1051. https://doi.org/10.1016/j.ecoleng.2010.04.017.

Horppila, J. & Nurminen, L. 2001 The effect of an emergent macrophyte (*Typha angustifolia* (L.)) on sediment

resuspension in a shallow north temperate lake. *Freshwater Biology* **46**, 1447–1455.
Jamwal, P. 2017 Fate of nutrients in human dominated ecosystems. *Resonance* **22**, 279–290.
Jamwal, P. 2018 Remediation of Contaminated Urban Streams: A Decentralized Ecological Wastewater Treatment Approach. In: *Water Remediation*. Springer, Singapore, pp. 29–41.
Jamwal, P., Md Zuhail, T., Raje Urs, P., Srinivasan, V. & Lele, S. 2015 Contribution of sewage treatment to pollution abatement of urban streams. *Current Science* **108**, 677–685.
Jumbe, A. S. & Nandini, N. 2009 Heavy metals analysis and sediment quality values in urban lakes. *American Journal of Environmental Sciences* **5**, 678.
Karim, M. R., Manshadi, F. D., Karpiscak, M. M. & Gerba, C. P. 2004 The persistence and removal of enteric pathogens in constructed wetlands. *Water Research* **38**, 1831–1837. https://doi.org/10.1016/j.watres.2003.12.029.
Kato, S. 2011 Green infrastructure for Asian cities: the spatial concepts and planning strategies. In: *Journal of the 2011 International Symposium on City Planning*. Korea Planners Association, pp. 161–170.
Kim, B. R. 1989 Effect of ammonia on COD analysis. *Journal (Water Pollution Control Federation)*, 614–617.
Le Dantec, C., Duguet, J.-P., Montiel, A., Dumoutier, N., Dubrou, S. & Vincent, V. 2002 Occurrence of mycobacteria in water treatment lines and in water distribution systems. *Applied and Environmental Microbiology* **68**, 5318–5325. https://doi.org/10.1128/AEM.68.11.5318-5325.2002.
Lekang, O.-I. & Kleppe, H. 2000 Efficiency of nitrification in trickling filters using different filter media. *Aquacultural Engineering* **21**, 181–199.
Lonnen, J., Kilvington, S., Kehoe, S. C., Al-Touati, F. & McGuigan, K. G. 2005 Solar and photocatalytic disinfection of protozoan, fungal and bacterial microbes in drinking water. *Water Research* **39**, 877–883. https://doi.org/10.1016/j.watres.2004.11.023.
Low, C. S. 2002 *Appropriate Microbial Indicator Tests for Drinking Water in Developing Countries and Assessment of Ceramic Water Filters*. PhD Thesis, Massachusetts Institute of Technology, Cambridge, MA, USA.
Malarvizhi, R., Venkateswarlu, Y. & Begum, S. S. 2010 Studies on removal of chromium (VI) from water using chitosan coated Cyperus pangorei. *Water Science and Technology* **62**, 2435–2441.
Mashauri, D. A., Mulungu, D. M. M. & Abdulhussein, B. S. 2000 Constructed wetland at the university of Dar es Salaam. *Water Research* **34**, 1135–1144. https://doi.org/10.1016/S0043-1354(99)00238-9.
Mell, I. C. 2010 *Green Infrastructure: Concepts, Perceptions and its use in Spatial Planning*. PhD Thesis, Newcastle University, Newcastle, UK. https://theses.ncl.ac.uk/dspace/handle/10443/914.
Morel, A. 2006 *Greywater Management in low and Middle-Income Countries*. Swiss Federal Institute of Aquatic Science and Technology, Dubenforf, Switzerland.
Pisoeiro, J., Galvão, A., Ferreira, F. & Matos, J. 2016 Potential for CSO treatment with horizontal flow constructed wetlands: influence of hydraulic load, plant presence and loading frequency. *Environmental Science and Pollution Research* **23**, 20591–20599.
Prominski, M., Stokman, A., Stimberg, D., Voermanek, H. & Zeller, S. 2012 *River. Space. Design: Planning Strategies, Methods and Projects for Urban Rivers*. Birkhäuser, Basel, Switzerland.
Ramachandra, T. V., Bhat, S., Cincy, V., Asulabha, K. S., Lakkangoudar, K. & Rahaman, M. F. 2015 *Fish Mortality In Jakkur Lake: Causes and Remedial Measures (ENVIS Technical Report No. 86)*. Centre for Ecological Sciences, Indian Institute of Science, Bangalore, India.
Ribot, M., von Schiller, D., Peipoch, M., Sabater, F., Grimm, N. B. & Martí, E. 2013 Influence of nitrate and ammonium availability on uptake kinetics of stream biofilms. *Freshwater Science* **32**, 1155–1167. https://doi.org/10.1899/12-209.1.
Suthar, S., Sharma, J., Chabukdhara, M. & Nema, A. K. 2010 Water quality assessment of river Hindon at Ghaziabad, India: impact of industrial and urban wastewater. *Environmental Monitoring and Assessment* **165**, 103–112.
Tekerlekopoulou, A. G. & Vayenas, D. V. 2008 Simultaneous biological removal of ammonia, iron and manganese from potable water using a trickling filter. *Biochemical Engineering Journal* **39**, 215–220.
Tortajada, C. 2016 Policy dimensions of development and financing of water infrastructure: the cases of China and India. *Environmental Science & Policy* **64**, 177–187.
Weerakoon, G., Jinadasa, K., Herath, G. B. B., Mowjood, M. I. M. & Van Bruggen, J. J. A. 2013 Impact of the hydraulic loading rate on pollutants removal in tropical horizontal subsurface flow constructed wetlands. *Ecological Engineering* **61**, 154–160.
Wu, S., Carvalho, P. N., Müller, J. A., Manoj, V. R. & Dong, R. 2016 Sanitation in constructed wetlands: a review on the removal of human pathogens and fecal indicators. *Science of the Total Environment* **541**, 8–22. https://doi.org/10.1016/j.scitotenv.2015.09.047.
Xu, W., Chen, J., Jian, Y., Pan, Z. & Mou, Z. 2018 Treatment of sewage using a constructed soil rapid infiltration system combined with pre-denitrification. *International Journal of Environmental Research and Public Health* **15**, 2005.
Yang, X. J., Tong, Y. M., Song, Y., Qi, W. K., Li, Y. Y. & Guo, Y. L. 2017 Domestic sewage and secondary effluent treatment using vertical submerged biological filter. In: *IOP Conference Series: Earth and Environmental Science*. IOP Publishing, Bristol, UK, p. 012067.

First received 11 July 2018; accepted in revised form 11 March 2019. Available online 21 March 2019